

**IBROOKHAVEN NATIONAL LABORATORY
PROPOSAL INFORMATION QUESTIONNAIRE
LABORATORY DIRECTED RESEARCH AND DEVELOPMENT PROGRAM**

PRINCIPAL INVESTIGATOR	Elke-Caroline Aschenauer	PHONE	4769
DEPARTMENT/DIVISION	Physics	DATE	04/05/2010
OTHER INVESTIGATORS	Brian Cole (Columbia University), Emlyn Hughes (Columbia University), Carla M. Vale (BNL), Marc Winter (IPHC-CNRS)		
TITLE OF PROPOSAL	CMOS-Pixel Vertex Detector for EIC		
PROPOSAL TERM (month/year)	From 10/2010	Through	10/2013

SUMMARY OF PROPOSAL

Description of Project:

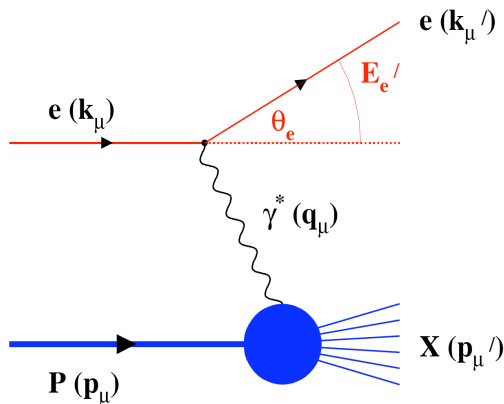
Introduction:

Even after many years of studying QCD in detail, the question "*How do we understand the visible matter in our universe in terms of the fundamental quarks and gluons of QCD?*" remains unanswered.

If it would be possible to answer the following questions, namely

- **What is the role of gluons and gluon self-interactions in nucleons and nuclei?**
- **What is the internal landscape of the nucleons?**
 - **What is the nature of the spin of the proton?**
 - **What is the three-dimensional spatial landscape of nucleons?**
- **What governs the hadronization process in the conversion of quarks and gluons into hadrons?**

these answers could provide the keys to understanding how matter is formed from the fundamental quarks and gluons of QCD.



Answering these questions needs a tool, which probes the structure of nucleons with high resolution. This can be achieved by studying nuclei and nucleons in deep-inelastic scattering (DIS), where a lepton scatters off the partons in a nucleon or nuclei via the exchange of a virtual photon γ^* , see Fig. 1. The squared four-momentum Q^2 of the virtual photon provides the resolution scale for probing the inner structure of nucleons and nuclei (increasing Q^2 = higher resolution)

A future Electron-Ion Collider (EIC) at BNL would have the worldwide unique ability to collide high-energy electron beams with high-energy ion

and polarized proton beams at RHIC. An EIC will provide access to those regions in the nucleon and nuclei where the structure is dominated by gluons. The electron energies are presently envisioned to begin at 4 GeV and be upgraded to 20 GeV at a later stage of the program.

There is a broad and rich physics program with e+A and e+p collisions, ranging from simple inclusive measurements, detecting only the scattered electron in DIS events to semi-inclusive measurements, detecting the scattered electron in coincidence with the hadronic final state as well as the complex topology of exclusive measurements, detecting the complete final state in diffractive events. For all of these event classes, it is crucial to detect the scattered electron and measure its energy and scattering angle with high precision, because the electron kinematics is directly related to the parton kinematics in the hard scattering. The success of each of these challenging measurements depends crucially on the energy and luminosity of the machine as well as on the performance of the detector.

A first design of the detector together with the accompanying software tools to evaluate the impact of the detector on physics observables (see Fig. 2 right) has been developed. The detector design is done in very close collaboration with the EIC group at CAD, in order to integrate the detector from the beginning into the IR design (see Fig. 2 left). This is essential, because several measurements (e.g. exclusive vector meson production) require the detection of the scattered intact beam proton. These scattered protons have a very small momentum difference compared to the initial beam energy (~ 10 MeV) and need therefore to be detected in special detectors integrated in the lattice of the machine.

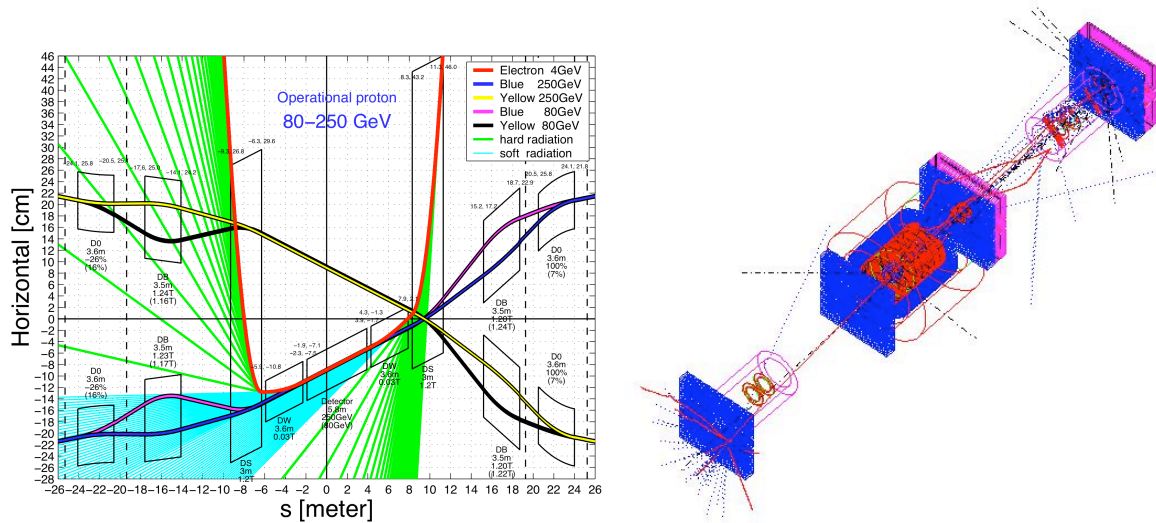


Figure 2: Left: Interaction region design with the detector integrated to the layout. The green lines and light blue band represent, respectively, hard and soft synchrotron radiation from the bent electron beam. The IR design already incorporates already methods to shield the detector from hard synchrotron radiation. This shielding is omitted in this picture. Right: Detector design with tracks from exclusive vector meson production.

Initial detector resolution simulations have clearly shown that it is extremely important to minimize the radiation length of the detector to preserve good momentum resolution ($\delta p/p \sim 2\%$) and angle reconstruction for the scattered electron and to reduce the rate of bremsstrahlung emission from electrons as they traverse the detector material. This is especially challenging, since it is desired to track the scattered electron down to momenta as small as 500 MeV. Another important feature of the detector is the need for precise vertexing to identify charmed and beauty mesons and baryons through their displaced decay vertices.

To achieve these requirements one needs an integrated design for the tracking detectors starting from the micro vertex detector to the vertex and large angle tracking detectors. A detailed and systematic study of silicon detection with ultra low radiation lengths is a requirement for the EIC detector program. The tracker must also be able to withstand the radiation doses, anticipated with the high luminosity running, which need still to be determined.

Plan for the tracking system for an EIC detector

As described in the previous section, the EIC detector should include a vertex detector that can track over a wide range of pseudo-rapidity and down to the lowest p_T allowed by the detector geometry and that is capable of reconstructing displaced vertices from heavy flavor decays. Traditionally, such detectors are implemented in two separate parts – a “barrel” layer that detects tracks out to $|\eta| \sim 2$ and an endcap composed of disks that extend the acceptance down to smaller polar angles (larger $|\eta|$). To achieve the performance needed to resolve displaced vertices from the primary vertex down to distances of $< 100 \mu\text{m}$, the barrel and end-cap will need at least three sensitive layers providing two-dimensional measurement of particle positions with resolutions $< 10 \mu\text{m}$ in both directions. The traditional technology choice for vertex detectors designed to measure heavy flavor decays is silicon hybrid pixel detectors. Such detectors have been used successfully at the Tevatron and are an integral part of the tracking systems for the ATLAS and CMS detectors. However, such detectors typically contain 100-300 μm of silicon and significantly more material in the separate readout chips resulting in typically $\sim 3\% - 10\%$ radiation length of material per layer. Such detectors are unsuitable for EIC applications – at least in the barrel and in the forward (electron direction) endcap detectors where the constraints on material budget necessary to limit electron bremsstrahlung are most severe.

In the last decade there has been significant progress in the development of Monolithic Active Pixel Sensors (MAPS) in which the active detector, analog signal shaping, and digital conversion take place in a single silicon chip (i.e. on a single substrate) (see [1] and references therein). These devices built using CMOS technology use an epitaxial layer as the active sensing element. Ionization deposited in the epitaxial layer is collected by N+ wells embedded in the epitaxial layer. The “pixel” pitch is determined by the location of the N wells so there is no need for actual segmentation of the detector as is done with traditional hybrid pixel detectors. As a result, CMOS pixel detectors can be built with very high segmentation, limited primarily by the space required for additional shaping and digital conversion elements.

The key advantage of CMOS MAPS detectors for an EIC detector is the reduced material required for the detector and the (on substrate) on-detector electronics. Such detectors have been fabricated and extensively tested (see e.g. [2]) with thicknesses of about 50 μm corresponding to 0.05% of radiation lengths. The charge collection N+ wells are coupled to transistors that provide a first amplification stage and the incorporation of additional amplification and discrimination stages in the same substrate has been successfully demonstrated [3]. As a result, the MAPS pixel chips can directly drive digital signals to off-detector data collection electronics. The lack of separate read-out chips and associated bonding reduces both the material budget of the detector and the complexity of detector assembly. The reduced ionization electron yield of CMOS detectors compared to thicker hybrid detectors is offset by the on-board amplification of the signal and the reduction in noise due to the thin, low-depletion active layer. As a result, the detectors can be operated with a signal-to-noise ratio of 20-30 at temperatures as high as 40° C [1]. The CMOS MAPS detectors operate with low power dissipation (estimate for EIC:

0.2 W/cm²). So it is likely that they could be operated in an EIC detector with only air-cooling thereby reducing further the material budget for the vertex detector.

There has been extensive development of the CMOS MAPS detector technology by Winter's group at Strasbourg (see [4] for overview of Strasbourg groups efforts), and ladders fabricated with sensors of similar geometry and functionality that might be required for the *barrel* part of a vertex detector are already being produced by the Strasbourg group. However, the actual incorporation of such detectors into an EIC detector will require matching the characteristics of a future sensor to the physics performance requirements of the EIC detector and will require extensive study of detector integration issues. In particular, EIC operation may require specific choices for the sampling rate and for the implementation of the readout.

For the *endcap* detector, true R&D may need to be done on fabrication of large sensors that would be needed to satisfy both geometric and material constraints. The most natural way to segment the disks in the endcaps would be to divide them up into ϕ segments with each segment consisting of a single sensor. By not dividing the wedges radially, the need for detector overlap and the corresponding increase in material would be obviated. Assuming that the extent of the disks in the radial direction would be at least 10 cm, sensors capable of covering a complete ϕ segment would be larger than the typical reticule (photomask) used at foundries. However, through a process called stitching it is possible to join reticules to fabricate larger devices. Such a procedure was developed by industry for CMOS light imagers, in particular for space applications, but has never been used for CMOS charged particle detectors, and demonstrating the use of the technology for CMOS MAPS sensors would not only help in the design of the vertex endcap detector capable of meeting the severe material constraints of an EIC detector, but would also provide a valuable advance in CMOS pixel sensor R&D.

Goals and Expected Results:

One of the goals of this LDRD is to build up expertise in handling and testing CMOS pixel detectors at BNL and at Columbia University Nevis Labs, to develop a proof-of-principle detector design for a CMOS-based silicon vertex detector capable of meeting the performance requirements of the EIC detector, and to pursue the development of a pixel sensors appropriate for a disk geometry.

The creation of laboratories at BNL and Columbia will be essential ingredients in the development of local expertise that will be required for the actual construction and operation of a CMOS pixel vertex detector for the EIC. By establishing a laboratory at Columbia, it will be possible to incorporate undergraduate students in the pixel effort, thereby providing a source of future expertise in this detector technology. In addition, Nevis provides a unique facility for testing silicon detectors, namely a high intensity x-ray source that is currently being used to test detectors for the NuStar satellite. This facility is not being fully utilized and would be available for carrying out tests of prototype detectors at Nevis at no cost beyond that required for mounting, powering, and reading out the detector.

The proof-of-principle design for the vertex detector should include

1. A detailed evaluation of the performance requirements for the vertex detector and demonstration that the required performance can be achieved using current CMOS sensors.

2. A study of the optimal geometry for pixel ladders for the barrel detector that will provide maximal geometric coverage while avoiding detector overlaps and an evaluation of the geometric constraints imposed by different readout solutions.
3. An evaluation of cooling and mechanical support requirements and methods of achieving these requirements in a minimal material budget.
4. Estimate of beam and physics backgrounds in the vertex detector and an evaluation of the constraints on the detector sampling time resulting from these backgrounds.

These design studies will be supported by GEANT-based MC studies detailing the performance of the detector and its impact on the physics program of an EIC.

For the forward disk shape detectors it is proposed to demonstrate a proof of principle of the stitching process, assuming a forward disk inner radius of 8 cm and an outer radius between 16 and 24 cm. The disk surface needs to be subdivided in as few as possible separate sensors in order to keep the material budget as low as possible. A rather natural set of dimensions of the sensitive area would be typically 2 cm width in its inner part and 4 to 6 cm width at its outer edge. Its radial extension would be in the range 8-16 cm. Such a surface is much larger than a typical reticule surface (about $2 \times 2 \text{ cm}^2$). Manufacturing a sensor of such a large surface requires an industrial procedure called "stitching". CMOS sensors are fabricated within standard mass production chip manufacturing processes, where the chip photolithography is realized over an exposure field (reticule) of about $2 \times 2 \text{ cm}^2$. A stepper allows replicating these reticules over the full wafer surface. By default, the chip die is therefore limited to the reticule size. The limitation imposed by the exposure field of lithography steppers may be overcome with the stitching technology, which allows the physical merger of multiple design structures onto a wafer during the photolithography process. This opens the door to fabricating sensors composed of millions or tens of millions of pixels and featuring dimensions similar to those of a complete 8" wafer. As it was never tried for charged particle pixel sensors, it is crucial to make the proof of principle of "stitching" within this project. The plan would be extending the area of an existing chip from $1 \times 2 \text{ cm}^2$ to a surface of about $5 \times 5 \text{ cm}^2$ (10M pixels with $16 \text{ }\mu\text{m}$ pitch). Their binary, zero-suppressed, read-out translates into a spatial resolution of about $3\text{-}3.5 \text{ }\mu\text{m}$. The expected read-out time is of the order of $300 \text{ }\mu\text{s}$, which for example would allow equipping a beam telescope with such sensors.

The sensor fabrication would be funded by other means (about 100 – 120 k\$ provided through IPHC-CNRS), but the overhead generated by the stitching costs (about 50 k\$) would be provided by the budget of this LDRD proposal.

In short, we propose to demonstrate the proof of principle of stitching in 2011-2012 by asking for 50 k\$ dedicated to this procedure, taking advantage of a chip submission, which is planned to launch in 1 or 2 years.

Challenges of the stitching prototyping:

The prototype will address all prominent issues generically inherent to large surface, small pixel sensors. They may either concern directly the stitching technique or follow from the large dimensions of the sensitive area. A short list of the issues addressed follows:

1. the precision of the stitching technique, which manifests itself at the reticule boundaries, should match the accuracy of the pixel and read-out circuitry design without introducing design discontinuities;

2. the sensor performance should be uniform over the complete sensitive area;
3. the fabrication process and the stitching technique should allow for a high yield;
4. capacitive and resistive effects consecutive to several centimeter long traces implemented in the sensor should not dilute its noise and read-out speed performances;
5. the read-out architecture adapted to a sensor of 10M pixels needs to be validated.

Contributions to the project from other sources:

The IPHC team contributing to the project has pioneered CMOS pixel sensors for charged particle tracking and has presently achieved the state of the art of this technology. It is currently developing this sensor technology for several subatomic physics experiments, including the STAR-PIXEL detector.

The team contribution to the project will come from its twelve years long experience of CMOS pixel sensors and from several of its current activities which are directly relevant to the project. It will include some dedicated deliverables.

The team is currently developing ultra-light pixelated ladders and fast, high resolution, radiation tolerant, CMOS pixel sensors, which will directly benefit to the project, including all the know-how accumulated on the sensors and their operation. The team is an active member of several international R&D collaborations, where issues such as high precision alignment are being studied, which will feed the project. The team runs numerous test benches, which can be used for the project, as well as beam telescopes, which it operates frequently at the CERN-SPS and at DESY. The staff needed for the beam test preparation and operation will be provided by IPHC. Moreover, the team will design, fabricate and test a sensor exploring stitching. It will also study the design of a CMOS sensor adapted to the forward disks of the experiment underlying the project.

Citations

- [1] *Monolithic active pixel sensors for fast and high resolution vertex detectors*, Gaycken G., *et al*, NIM A560, 44 (2006).
- [2] *CMOS pixel sensor development : a fast read-out architecture with integrated zero suppression*, Hu-Guo C., *et al*, Journal Of Instrumentation 4, 04012 (2009).
- [3] *Monolithic active pixel sensors with on-pixel amplification and double sampling operation*, DEPTUCH G. *et al*, NIM A512, 299 (2003).
- [4] <http://www.iphc.cnrs.fr/-CMOS-ILC-.html>

BUDGET REQUEST BY FISCAL YEAR

Physics Department

CMOS-Pixel Vertex Detector for EIC

Elke-Caroline Aschenauer

The project should run from 10/2011 till 10/2013

The following budget is requested

1. Postdoc for 3 years	210k\$
2. Undergraduate students to work on testing pixel ladders	50k\$
3. Equipment for silicon test stand at BNL and at NEVIS gamma beam facility	50k\$
4. Run to produce prototype pixel detector suitable for disc shaped detectors	50k\$
5. Material cost to fabricate pixel ladders (copies from the ones at IPHC-CNRS)	50k\$
6. Travel costs to go to test beams at CERN and for group meetings	40k\$
7. Cost for a workshop and visitors	40k\$

Total Cost over 3 years: 500k\$

VITA
Elke-Caroline Aschenauer

Education and degrees:

1990 – 1994 Ph.D. Swiss Federal Institute of Technology Zürich, CH
1984 – 1989 Major in Physics at the Friedrich-Alexander-University, Erlangen, D
1986 'Vordiplom' in Physics

Career:

1994 – 1996: Human Capital and Mobility Fellowship of the European Community
1994 – 1995 Research associate at the NIKHEF-K, Amsterdam, NL
1995 – 1996 Research associate at the Department of Physics of the
University of Gent, Belgium
1996 – 2001: Post-Doctoral Fellow at DESY, Germany
2001 – 2006: Staff Scientist at DESY, Germany
2007 – 2009: Senior Staff Scientist at JLAB, USA
2009 – present: Staff Scientist at BNL, USA

Awards and (Inter)National Service:

200 Academic research prize of the University of Regensburg Prof.-Hess-Dozentur
2009 – present: member of the DESY physical review committee
2009 – 2012: member of the BMBF (German funding agency) committee reviewing applications
in nuclear physics (2nd 3 year period)

Main achievements:

- RHIC Spin Group Leader and Co-Chair BNL EIC Taskforce
- As the Hall-D Group Leader and project leader for the Hall-D part of the 12 GeV upgrade. In the two years at JLab, I build up the JLab-group and stewarded the project through all the reviews needed for CD-2 and CD-3
- During my time at DESY, I was responsible for designing and building the photon detector for the HERMES RICH, as well as commissioning and being the local expert (1998-2006) for the detector. The HERMES RICH made a significant difference to the physics capabilities of HERMES.
I was the HERMES Run-coordinator and Deputy Spokesperson from 2000-2003 and the Hermes Spokesperson from 2003-2006

1. HUMAN SUBJECTS (Reference: DOE Order 443.1)

Are human subjects involved from BNL or a collaborating institution? Human Subjects is defined as “A living individual from whom an investigator obtains either (1) data about that individual through intervention or interaction with the individual, or (2) identifiable, private information about that individual”.

N

If **yes**, attach copy of the current Institutional Review Board Approval and Informed Consent Form from BNL and/or collaborating institution.

Y/N _____

2. VERTEBRATE ANIMALS

Are live, vertebrate animals involved?

N

If **yes**, attach copy of approval from BNL’s Institutional Animal Care and Use Committee.

Y/N _____

Y/N _____

3. NEPA REVIEW

Are the activities proposed similar to those now carried out in the Department/Division, which have been previously reviewed for potential environmental impacts and compliance with federal, state, local rules and regulations, and BNL’s Environment, Safety, and Health Standards? (Therefore, if funded, proposed activities would require no additional environmental evaluation.)

Y

Y/N _____

If **no**, has a NEPA review been completed in accordance with the Subject Area National Environmental Policy Act (NEPA) and Cultural Resources Evaluation and the results documented?

Y/N _____

(Note: If a NEPA review has not been completed, submit a copy of the work proposal to the BNL NEPA Coordinator for review. No work may commence until the review is completed and documented.)

4. ES&H CONSIDERATIONS

Does the proposal provide sufficient funding for appropriate decommissioning of the research space when the experiment is complete?

Y/N Y _____

Is there an available waste disposal path for project wastes throughout the course of the experiment?

Y
 Y/N _____

Is funding available to properly dispose of project wastes throughout the course of the experiment?

Y
 Y/N _____

Are biohazards involved in the proposed work? If yes, attach a current copy of approval from the Institutional Biosafety Committee.

Y/N N _____

Can the proposed work be carried out within the existing safety envelope of the facility (Facility Use Agreement, Nuclear Facility Authorization Agreement, Accelerator Safety Envelope, etc.) in which it will be performed?

Y/N Y

If **no**, attach a statement indicating what has to be done and how modifications will be funded to prepare the facility to accept the work.

5. TYPE OF WORK

Select Basic, Applied or Development Development

6. LINK TO LABORATORY STRATEGIC INITIATIVES

Identify below if the proposal is in support of RHIC, the Light Source, or any of the Strategic Initiatives that can be found listed at the LDRD web site, www.bnl.gov/ldrd.
RHIC, eRHIC, MeRHIC

7. POTENTIAL FUTURE FUNDING

Identify below the Agencies and the specific program/office, which may be interested in supplying future funding. Give some indication of time frame.

DOE NP, NSF

APPROVALS

Department /Division Administrator _____
Print Name

Department Chair/Division Manager _____
Print Name

Cognizant Associate Director _____
Print Name

COST ELEMENT	FISCAL YEAR 2011	FISCAL YEAR 2012	FISCAL YEAR 2013	TOTAL COST
Labor* Fringe Total Labor Organizational Burden @ ____ %				
DISTRIBUTED TECHNICAL SERVICES				
Materials Supplies Travel Services Total MST Materials Burden @ ____ %				
TECHNICAL COLLABORATORS/ CONSULTANTS				
Sub-contracts Contracts Burden @ ____ %				
Electric Power Other (specify)				
Traditional G&A @ ____ % Common Support G&A @ ____ %				
TOTAL PROJECT COST				
*Labor (give levels of effort with names, or if unknown indicate TBD) <u>Scientific & Professional</u> <u>Post Doc</u> <u>Other</u>				
<u>Note:</u> The Budget Office covers 20% of the Post Doc's salary/fringe.				
List all Materials Costing Over \$5,000				